NASA-CR-195767

IN-92-CR
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PROGRESS REPORT

FOR CONTRACT NASW-4814

CORONAL ABUNDANCES AND THEIR VARIATION

Date: 15 April 1994

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ABSTRACT

This contract supports the investigation of elemental abundances in the solar corona, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer on the *Solar Maximum Mission.* The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, and information on the extent and circumstances of their variability. This report is a summation of the data analysis and reporting activities which occurred during the first ten months of the contract, 15 June 1993 to 15 April 1994.

Subject terms: Solar corona, X-ray spectra, elemental abundances, abundance variability

I. INTRODUCTION

This is a progress report for contract NASW-4814. It is being submitted two months before completion of the first year of the contract to permit timely evaluation of progress and, it is hoped, timely continuation of funding for the next year. It includes and supersedes material submitted in a semi-annual report in December 1993.

The contract resulted from an award under NASA's Supporting Research & Technology Program after peer review of a proposal submitted by the Principal Investigator (PI) in August 1992 in response to NASA Reseach Announcement NRA-92-OSSA-10. Notification of the award was given in February 1993 and funding began in June 1993. The current investigation is a continuation and an extension of a pilot study of coronal abundances begun as a *Solar Maximum Mission* Guest Investigation (GI) by the same PI.

The contract supports an investigation of elemental abundances in the outer atmosphere of the Sun, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer (FCS) on the *Solar Maximum Mission (SMM)*, a NASA mission dedicated to solar observations from 1980 through 1989. This instrument acquired an excellent data base for studying the relative amounts of oxygen, neon, magnesium, and iron in solar active regions in various states of evolution and activity. The project includes analysis of this data base to decouple the effects of temperature and abundance, to assess different theoretical calculations of spectral line intensities for use in the study, and to account for the possible effects of opacity due to resonance scattering of certain bright lines. The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, information on the extent of their variability, identification of possible correlations of variability with active region properties, and clarification of a possible association between abundance variability and active region dynamics.

II. SCIENTIFIC BACKGROUND

Knowledge of solar elemental abundances is essential for correct interpretation of plasma diagnostic information from spectral and image data. Also, an assumed set of abundances is implicit in many aspects of astrophysical data analysis, such as calculations of energetics and radiative loss rates, and comparisons of relative emission in different wavebands to assess possible emission mechanisms. It has recently become apparent that a single set of abundances does not apply throughout the solar atmosphere, and that in some cases order of magnitude variability is found, so that many previous analyses must be reconsidered. In addition to these practical problems, it now appears that there are systematic differences in the average composition of the corona compared to the photosphere, and some details of coronal abundance variability might give important clues to the fundamental problems of coronal heating and mass supply. A talk discussing the implications of coronal abundance variations was presented by the PI at the Kofu meeting in Japan last September (see §IV and attached preprint).

Much of the observed variation in abundances between the photosphere and the solar wind and solar energetic particles (SEPs) is associated with the first ionization potential (FIP) of the elements, in the sense that elements with low FIP are enhanced in SEPs and the solar wind relative to high-FIP elements, as compared with photospheric composition. Although there is no convincing model yet available, the idea is that some element separation mechanism operates in a temperature regime of about 10,000 K where low-FIP elements are ionized while high-FIP elements remain neutral. However, spectroscopic data from *SMM* and other spaceraft show that coronal abundances in closed coronal structures present a more complex story than a simple two-step distribution of abundances (of high- vs. low-FIP) relative to photospheric values. An invited review of the coronal spectroscopic results will be given by the PI in the summer (see §IV and attached abstract) if the contract is renewed.

The *SMM* GI pilot study examined the behaviors of two low-FIP elements, Mg and Fe, and two high-FIP elements, O and Ne, in active region plasma in closed coronal loops. A statistical analysis showed that the ratio of the low-FIP Fe to the high-FIP Ne appeared to vary by a factor of 5 or more, spanning a range which included the photospheric and the nominal coronal values. The other low-FIP/high-FIP ratios also seemed to vary at least between the photospheric and nominal coronal values and both the low-FIP/low-FIP ratio Fe/Mg and the high-FIP/high-FIP ratio O/Ne also showed significant variability. Several issues arose which needed to be addressed in a more extensive study before the work could progress. To date the present investigation has been attacking two of those issues.

III. CURRENT PROGRESS

During the reporting period, 15 June 1993 to 15 April 1994, the PI has concentrated on two problem areas: (a) diagnosing and quantifying the role of resonance scattering in the measured line intensities, and (b) exploring the various temperature diagnostics available so that temperature effects can be accurately deconvolved from abundance effects in variable line ratios. If resonance scattering is important, it complicates both the abundance study and the analysis of the temperature diagnostics involving affected lines. Hence the impact of resonance scattering has had to be sorted out before other progress can me made. However, the resonance scattering itself can provide a way to normalize the relative abundances yielded by the line ratios, as shown in §§III.B.1.

A. Resonance Scattering

Schmelz, Saba, and Strong (1992) suggested that the bright Fe XVII line at 15.01 Å, which featured importantly in the pilot abundance study analysis, might be much more affected by resonance scattering than previous work by Rugge and McKenzie (1985) had indicated. In FCS active region data, the flux of the 15.01 Å line appeared to be depleted by about a factor of two to three below predicted theoretical values compared to other bright resonance lines. Schmelz *et al.* found that resonance scattering could deplete the observed flux in the 15.01 Å substantially for plausible active region conditions, while the effect on other lines examined could still be less than or comparable to the measurement uncertainties.

However, Waljeski *et al.* (1994) argue that, if the Fe XVII opacity is sufficiently high, other lines such as O VIII and Ne IX could also be significantly affected. In such a case, the effects of resonance scattering must be taken explicitly into account for all of the lines in deriving relative abundances from the measured line flux ratios. By considering two Fe XVII lines affected by scattering, the line at 15.01 Å and another at 15.25 Å with about one fourth the opacity, Waljeski *et al.* found about a factor of two higher scattering opacities for one of the active regions considered by Schmelz *et al.*

The magnitude of the effect of resonance scattering in the FCS data and the impact on the derived abundance variability is being assessed in two ways. To avoid ambiguities introduced by unknown abundances, five bright Fe XVII lines covered by the FCS spectra are intercompared. (See FCS Channel 1 spectrum in Figure 1.) The various theoretical calculations available for these lines are being examined with the assistance of Dr. Anand Bhatia at the Laboratory for Astronomy and Solar Physics at Goddard, who has made some of the calculations. The theoretical line ratios for pairs of these lines other than the forbidden line at 17.10 Å should be accurate to about 20% (Bhatia, private communication), although the spread between the recent calculations by Bhatia & Doschek (1992) and Cornille *et al.* and the older calculations by Mewe *et al.* (1985) and Smith *et al.* (1985) are greater than this for some of the line ratios. Two of these lines, one at 16.78 Å and one at 17.05 Å, have opacities which are a small fraction of that of the 15.01 Å line (4 and 5%, respectively – see the last column in Table 1.)

Using the combination of the 16.78 Å line and the 15.01 Å line has less uncertainty than using the ratio of the 15.25 Å line to the 15.01 Å line since the 16.78 Å line can be treated as optically thin, and the expected depletion of the 15.25 Å line is comparable to the uncertainties from measurement and the predicted line ratio uncertainty. From the ratio of the 16.78 Å line to the 15.01 Å line, the depletion of the 15.01 Å line can be found directly by comparing the observed with theoretical ratios. The opacity of the line can then be calculated by using the tabulated results of Kastner & Kastner (1990), who calculated the optical depth at line center of a Doppler-broadened line which corresponds to the escape probability from a homogeneous mixture of emitters and absorbers. This relation has been plotted in Figure 2 for $\tau < 3$. The observed depletion of the 15.01 Å line for NOAA Active Region 4901 (the region studied by Waljeski *et al.*) is about a factor of 2, which corresponds to $\tau \simeq 2.5$ (as opposed to $\tau \simeq 4.2$ found by Waljeski *et al.*). The opacities for the other lines in the study can then be scaled from τ for the 15.01 Å line according to Table 1 (for "adopted coronal abundances" of Meyer 1985), and the respective depletions found from the plot as [1 - escape probability]. For "coronal" abundances, the next most affected line is O VIII at 18.97 Å, which shows a 20% depletion (for $\tau \simeq 0.68$), comparable to the measurement uncertainty.

Although the resonance scattering opacities appear to be negligible for FCS lines other than the Fe XVII line at 15.01 Å for the nominal "coronal" composition, McKenzie & Feldman (1991) and Saba & Strong (1993) have reported that some active regions appear to show photospheric ratios for at least some lines. Since the abundances of the high-FIP elements are a factor of 3 to 4 higher relative to the low-FIP elements than for coronal composition, the O VIII and Ne IX lines would have opacities a factor of 3 to 4 higher relative to the Fe XVII 15.01 Å line than the values shown in Table 1: the O VIII line would have an opacity comparable to that of the Fe XVII 15.01 Å line and the Ne IX line could have $\tau \sim 1$ and be depleted by $\sim 30\%$. Thus, the effect of resonance scattering for the FCS data with apparent near-photospheric ratios must be reexamined. This analysis is currently underway.

A fraction of the pilot abundance analysis was repeated using the Fe XVII line at 16.78 Å which can be treated as optically thin to scatter. Figure 3 shows a comparison between the abundance-diagnostic ratio Fe XVII/Ne IX ratios plotted against the temperature-diagnostic ratio Fe XVIII/Fe XVII between (a) the result using Fe XVII at 15.01 Å, and (b) the result when the Fe XVII line at 16.78 Å is substituted on both axes. Qualitatively the two plots look quite similar, although detailed differences can be found. Certain data points move between one plot and the other, but the scatter is about the same and hence the bulk of the observed scatter in the data cannot be due to resonance scattering. However, it appears that resonance scattering could introduce a systematic offset in the actual abundance ratios or a preferential effect for the data points near the bottom of the plot, which correspond to near- photospheric ratios.

Work on resonance scattering and on comparison of the theoretical and measures Fe XVII line intensities will continue in the remainder of the reporting period. A talk on the reexamination of resonance scattering in the abundance analysis will be given during the nominal reporting period at the joint AGU/SPD meeting in Baltimore in May (see §IV and attached abstract).

B. Diagnostic Tools

1. Resonance scattering as a tool

Although resonance scattering adds a complication to the FCS abundance analysis, it also provides a method for normalizing the relative abundances with respect to hydrogen, as reported by Waljeski *et al.* (1994). (This approach developed in part from extensive discussion between the PI – a coauthor – and the first author.) The optical depth at line center, τ, to scattering can be determined from the observed flux depletions of a pair of the Fe XVII lines as discussed above. But τ can also be calculated (Acton 1978) as:

$$\tau = 9.31 \times 10^{-18} f_{\rm lu} \cdot \frac{n_i}{n_{\rm Fe}} \cdot \frac{n_{\rm Fe}}{n_H} \cdot \lambda_A \int \left(\frac{M_A}{T_D}\right)^{1/2} n_e dl$$

where λ_A is the wavelength of line center in Angstroms, $f_{\rm lu}$ is the absorption oscillator strength of the transition from the lower level l to the upper level u; n_i is number of iron ions in the relevant ionization state, $n_{\rm Fe}$ is the total number of the iron atoms, n_e is the number of electrons, and n_H is the number of hydrogen atoms; M_A is the mass of Fe in AMU, T_D is the Doppler temperature of the line profile, and $\int n_e dl$ is the integrated electron density along the line of sight. The ion fraction n_i/n_{Fe} can be calculated as a function of temperature. At $T_e = 3$ MK, $n_{\rm FeXVII}/n_{\rm Fe}$ is calculated to be 0.776 by Arnaud & Rothenflug (1985) and 0.631 by Arnaud & Raymond (1992). Thus all quantities are known or can be calculated or measured, except for the factor $n_{\rm Fe}/n_H$ (the abundance of iron relative to hydrogen) and the integral of the column density. But, for an Fe XVII line unaffected by resonance scattering, the line intensity is proportional to the factor $n_{\rm Fe}/n_H$ times the column emission measure, EM $= \int n_e{}^2 dl$, times factors involving atomic data and constants. If the density is assumed to be uniform or nearly so, then $\int n_e dl \simeq n_e L$ and $\int {n_e}^2 dl \simeq {n_e}^2 L$, where L is the path length. Thus (*cf.* Schmelz *et al.*), one can write:

$$\tau = \text{constant} \times \frac{n_{\text{Fe}}}{n_H} \cdot \frac{\text{EM}}{n_e} = \text{constant}' \times \frac{I_L}{n_e},$$

where the factor $(n_{\text{Fe}}/n_H) \cdot \text{EM}$ is gotten from I_L, the measured intensity of an iron line unaffected by scattering, and a value for τ is obtained by comparing a resonantly scattered line to an unaffected line (or a more affected line with a less affected line).

Solving this expression for n_e and estimating the path length L from imaging data then allows one to constrain the ratio n_{Fe}/n_H in the initial equation for τ and thus scale the other relative abundances with respect to hydrogen also. From a derived τ of 4.2 (+1.3,-1.0) for Fe XVII at 15.01 Å, Waljeski *et al.* found $n_{\text{Fe}}/n_H = 3.2(+2.0, -2.1) \times 10^{-4}$, a factor of 8 ± 5 times the ratio originally adopted by Meyer (1985) under the assumption that hydrogen scales as a low-FIP element. Their value of τ seems too large by about a factor of 2 based on recent work by the PI (to be reported at the Spring 1994 AGU/SPD meeting). For $\tau \sim 2$, the value of $n_{\text{Fe}}/n_H \sim 1.6 \times 10^{-4}$, or about 4 times the ratio adopted by Meyer. More spectra need to be examined and a proper error analysis done, but this preliminary result suggests that the low-FIP elements are enhanced relative to hydrogen in the corona by about a factor of 4 comapred to their photospheric values.

Although this method produces large uncertainties in the absolute abundances, it provides an estimate of the absolute abundances that appears to be difficult to achieve by other means for active region coronal plasma. (At active region temperatures, free-bound emission dominates the free-free contribution to the continuum, so that abundances relative to hydrogen cannot be obtained from line-to-continuum ratios even when the instrumental background is a small fraction of the continuum.) The absolute abundances are of great interest for modeling the coronal elemental differentiation, and also essential for obtaining normalized emission measures, which are needed for interpreting the data and for astrophysical calculations, as noted above in §II.

2. Temperature diagnostics

Work has begun on comparing the various temperature diagnostic line ratios available in the FCS data base. The most sensitive temperature diagnostic to use is a ratio of the Fe XVIII line at 14.24 Å with one of the Fe XVII lines. However, to make use of this ratio, one needs to have good values for the fractions of iron in the ionization states Fe^{+17} and Fe^{+16}. Unfortunately, the ionization balance calculations that predict these ion fractions as a function of temperature have recently come into question. New calculations have been proposed by Arnaud and Raymond (1992) as an improvement over the previous calculations of Arnaud and Rothenflug (1985 Astrophys. J. Suppl. Series, 60, 425), which were used in the pilot study. The two sets of calculations yield values of temperature for a given Fe XVIII/Fe XVII flux ratio, which translates into different relative abundance ratios for given values of flux ratios for the lines used in the study. A comparison of the Fe XVIII/Fe XVII temperature diagnostic with diagnostics from the Mg XI and Ne IX triplets and with the ratio of Mg XII/Mg XI is in progress. Although these ratios are less sensitive to temperature, they should give a handle on which of the two sets of iron ionization balance calculations are more consistent with the FCS data. To date, the older Arnaud & Rothenflug ion fractions seem more consistent with the FCS data, but the impact of Fe XVII resonance scattering still needs to be accounted for more completely.

Now that the resonance scattering study has progressed, it should be more feasible to proceed with the temperature diagnostic analysis. The goal is to be able to convert the various line flux ratios to relative abundance ratios by dividing out the temperature response. Ongoing dialogues have also been established with several other groups who are comparing predictions of the iron ionization balance calculations with their own data or who are examining the calculations from first principles. This work will continue in the remainder of the reporting period.

A different approach to the abundance analysis which should provide complementary information to, and verification of, the line-ratio analysis is just now being undertaken in parallel to the continuing line-ratio analysis. This method involves using the calculated emissivities for each line as a function of temperature to overlay the respective emission measure curves of the lines. This requires taking into account the effect of resonance scatter (by using an Fe XVII line ratio to obtain the opacity of the 15.01 Å line, and scaling the other lines accordingly) and adjusting the "source" line intensities as appropriate, and assuming a set of relative abundances, which can be initially taken to be the "adopted coronal" values, for example (or the initial abundance guesses can be guided by the line ratio results). If the plasma is approximately isothermal (to within the FCS temperature resolution), as is likely to be the case for stable active region conditions, then the assumed relative abundances and any resonance scattering effects for the O VIII, Ne IX, and Mg XI lines can be iterated until the overlying curves for each line all intersect in a single location on the emission measure/temperature plot.

In a simpler form, this approach has been used successfully in a number of previous analyses, including the recent work of Waljeki *et al*, where the analysis included the emission measure curves of broadband data as well. The advantages of combining this method with the current analysis are (i) that it provides a result that is less sensitive to any specific temperature diagnostic and (ii) that it makes it easier to keep track of the joint relative abundances of the four elements O, Ne, Mg, and Fe, without having to explicitly divide out the temperature dependences. In turn, this will guide the deconvolution of temperature and abundance effects which is the goal of the line-ratio analysis. This combined approach will be exploited vigorously as the focus of the next reporting period if the contract is renewed.

IV. PUBLICATIONS AND PRESENTATIONS:

During the reporting period, the following presentations were made under this contract, to report and publicize initial findings and to obtain feedback from the community to refine plans for future work:

SMM Flat Crystal Spectrometer Measurements of Solar Active Region Abundances: Variations on the FIP theme: J.L.R. Saba and K.T. Strong, 24th meeting of the Solar Physics Division of the A.A.S., Stanford, California, 13-16 July 1993.

An Abundance of New Information for Astrophysics from the Solar Corona: J.L.R. Saba, Laboratory for Astronomy & Solar Physics seminar at Goddard Space Flight Center, 30 September 1993.

A camera-ready conference paper entitled *Implications of Coronal Abundance Variations*, by Julia L.R. Saba and Keith T. Strong, was submitted 15 January 1994 for publication in proceedings of the Kofu Symposium on a "New Look at the Sun with Emphasis on Advanced Observations of Coronal Dynamics and Flares – What Do We See with Yohkoh and Nobeyama Radioheliograph," held 6-10 September 1993 in Kofu, Japan. A copy of the paper is attached to this report. A talk on the same topic was presented at the symposium, attendance at which was supported by another contract.

During the reporting period, Saba made extensive contributions to the paper *The Composition of a Coronal Active Region*, by K. Waljeski, D. Moses, K.P. Dere, J.L.R. Saba, K.T. Strong, D.F. Webb, and D.M. Zarro, which has been accepted for publication in the Astrophysical Journal in July 1994.

An extended abstract for a talk at the joint American Geophysical Union–American Astronomical Society/Solar Physics Division Meeting in Baltimore, Maryland, in May 1994 has been submitted on *A Reexamination of the Impact of Resonance Scattering on FCS Active Region Abundance Measurements*. A copy of the abstract is attached. This talk will be given during the nominal reporting period.

An abstract entitled *Spectroscopic Measurements of Element Abundances in the Solar Corona: Variations on the FIP Theme* has been submitted for the 30th Assembly of the Committee on Space Research (COSPAR) to be held in Hamburg, Germany in July 1994. The paper will be an invited review, to be given in Session E2.1 on *Element Abundance Variations in the Sun and the Heliosphere*. A copy of the abstract is attached. Permission for foreign travel under the contract to attend the meeting is being sought in separate documentation.

A paper reporting on results of the FCS abundance study, taking into account the effects of resonance scattering and comparing the use of different ionization balance calculations, is being prepared for submission to the Astrophysical Journal.

REFERENCES:

Acton, L. W., 1978, Astrophys. J. 225, 1069

Arnaud, M., & Raymond, J. 1992, Astrophys. J., 398, 394

Arnaud, M., & Rothenflug, R., 1985, Astron. Astrophys. Suppl. Ser. 60, 425.

Bhatia, A.K., and Doschek, G.A., 1992, Atomic Data and Nuclear Data Tables, 52, 1.

Kastner, S.O., & Kastner, R.E., 1990, J. Quant. Spectrosc. Rad. Transf., 44(2), 275.

McKenzie, D.L., & Feldman, U. 1992, Astrophys. J., 389, 764.

Mewe, R., Gronenschild, E.H.B.M., and van den Oord, G.H.J., 1985, Astron. Astrophys. Suppl. Ser., 62, 197.

Meyer, J.-P., 1985, Astrophys. J. Suppl, 57, 173.

Rugge, H.R., & McKenzie, D.L., 1985, Astrophys. J., 297, 338.

Saba, J.L.R., and Strong, K.T., 1993, Adv. Space Res. 13, no. 9, 391.

Schmelz, J.T. Saba, J.L.R., and Strong, K.T., 1992, Astrophys. J., 398, L115.

Smith, B.W., Raymond, J.C., Mann, J.B., & Cowan, R.D., 1985, Astrophys. J., 298,898.

Waljeski, K., Moses, D., Dere, K.P., Saba, J.L.R., Strong, K.T., Webb, D.F., Zarro, D.M., 1994, Astrophys. J., 429, in press.

Table 1 ATOMIC PARAMETERS FOR LINES USED IN STUDY

Ion	Transition	λ (Å)	f_{lu} [1]	log(A) [2]	A_i [3]	M [4]	κ_0	τ/τ_0
O VIII	$1s\,^2S_{1/2} - 2p\,^2P_{1/2}, ^2P_{3/2}$	18.97	0.44	8.39	0.316	16.0	$9.2 \times 10^{-21}\, n_e$	0.271
Ne IX	$1s^2\,^1S_0 - 1s\,2p\,^1P_1$	13.46	0.723	7.55	0.676	20.2	$4.0 \times 10^{-21}\, n_e$	0.117
Mg XI	$1s^2\,^1S_0 - 1s\,2p\,^1P_1$	9.17	0.745	7.57	0.955	24.3	$4.5 \times 10^{-21}\, n_e$	0.113
Fe XVIII	$1s^2 2s^2 2p^5\,^2P_{3/2} - 2p^4 3d\,^2D_{5/2}, ^2P_{3/2}$	14.2	1.5	7.59	0.132	55.8	$3.1 \times 10^{-21}\, n_e$	0.092
Fe XVII	$1s^2 2s^2 2p^6\,^1S_0 - 2p^5 3d\,^1P_1$	15.01	2.66	7.59	0.776	55.8	$3.4 \times 10^{-20}\, n_e$	=1.000
Fe XVII	$1s^2 2s^2 2p^6\,^1S_0 - 2p^5 3d\,^3D_1$	15.26	0.593	7.59	0.776	55.8	$7.7 \times 10^{-21}\, n_e$	0.229
Fe XVII	$1s^2 2s^2 2p^6\,^1S_0 - 2p^5 3s\,^3P_1$	16.78	0.101	7.59	0.776	55.8	$1.5 \times 10^{-21}\, n_e$	0.044
Fe XVII	$1s^2 2s^2 2p^6\,^1S_0 - 2p^5 3s\,^1P_1$	17.05	0.123	7.59	0.776	55.8	$1.8 \times 10^{-21}\, n_e$	0.052

[1] Absorption Oscillator Strength (from Bhatia & Doschek 1992 for Fe XVII; from Mewe et al. 1985 for other ions)

[2] Abundance relative to H ("adopted coronal" abundances from Meyer 1985)

[3] Temperature dependent ion fraction (Arnaud & Rothenflug 1985)

[4] Mass in atomic mass units

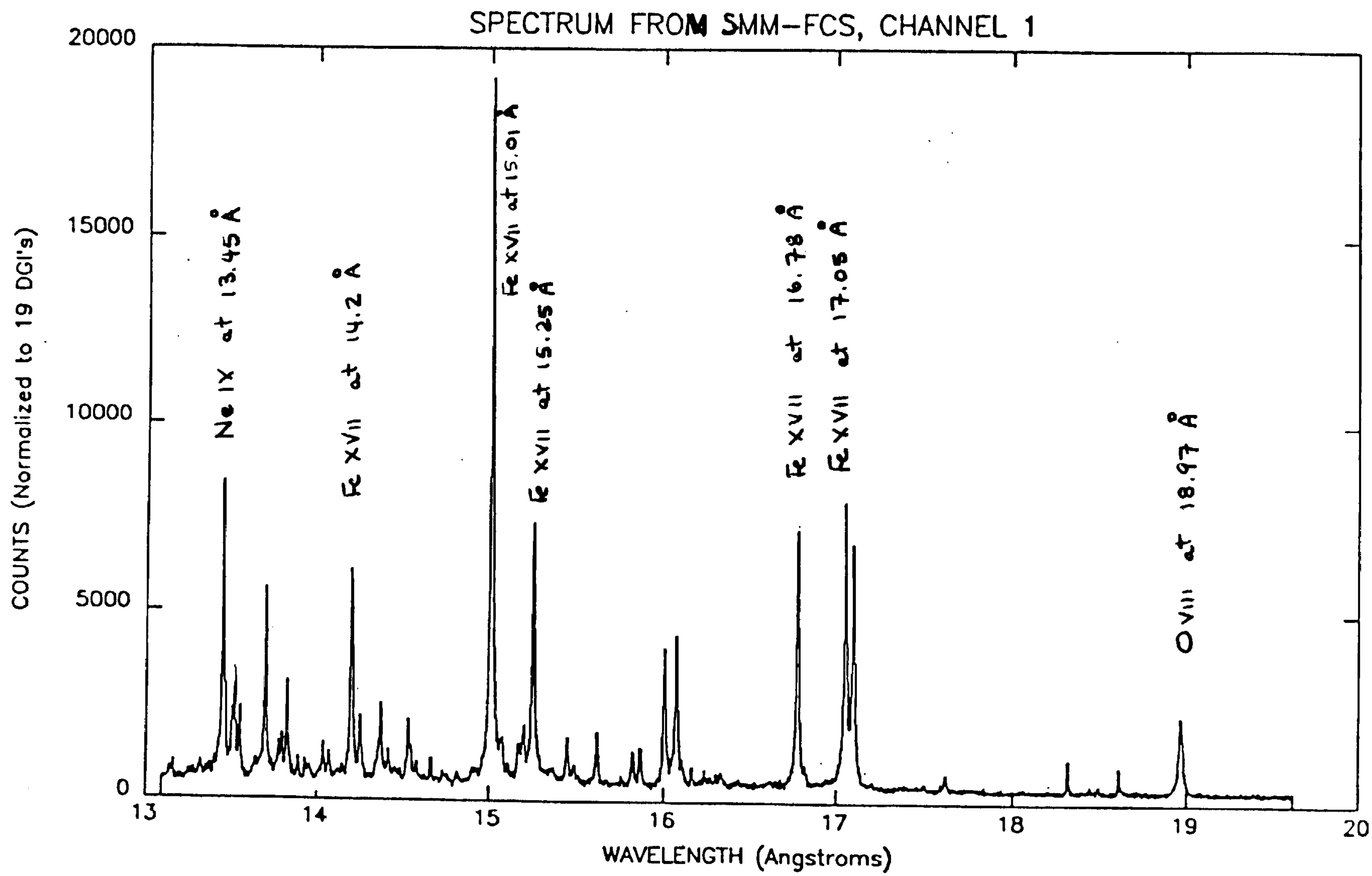


Figure 1 : FCS Active Region Spectrum, with some key lines in abundance study annotated.

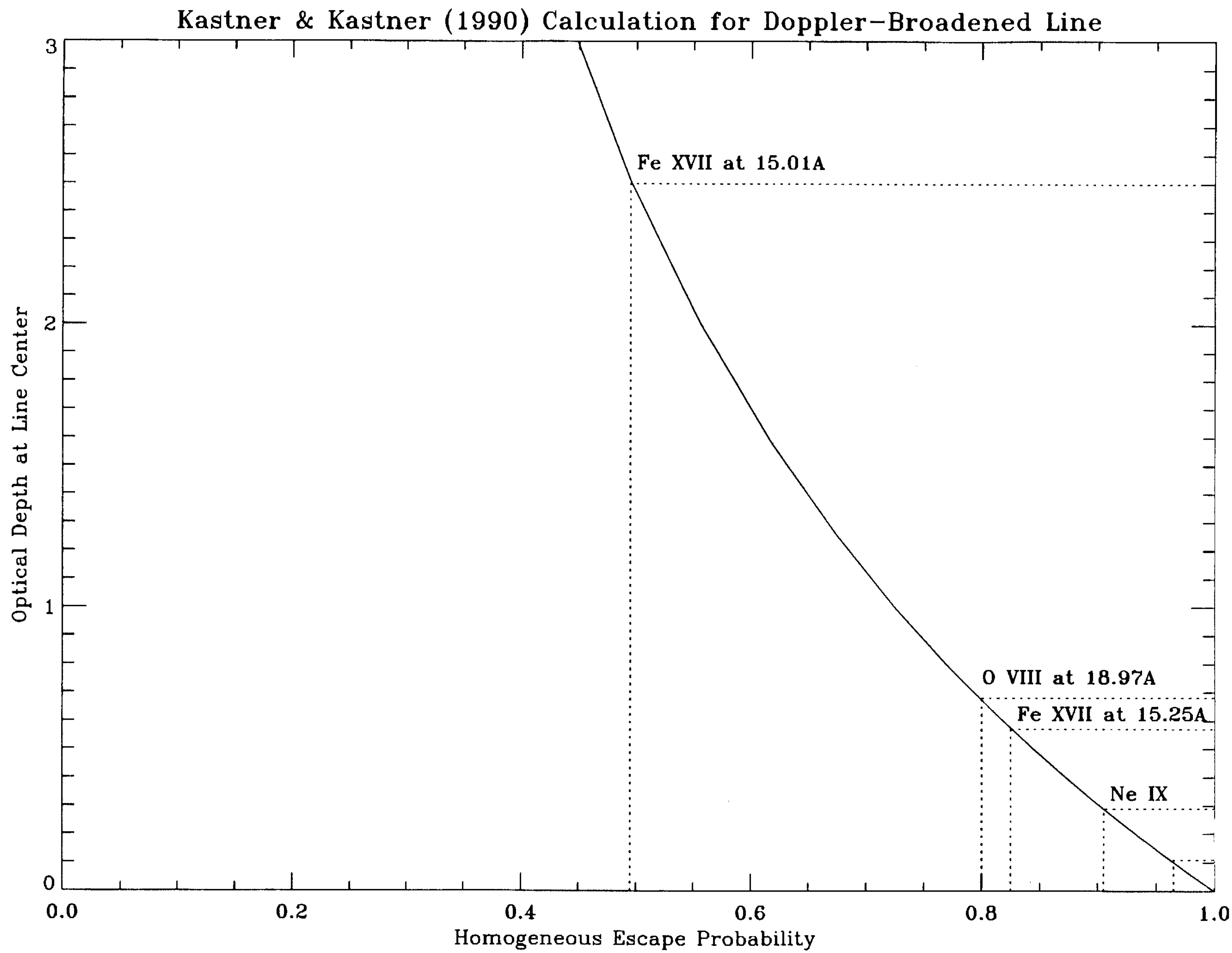
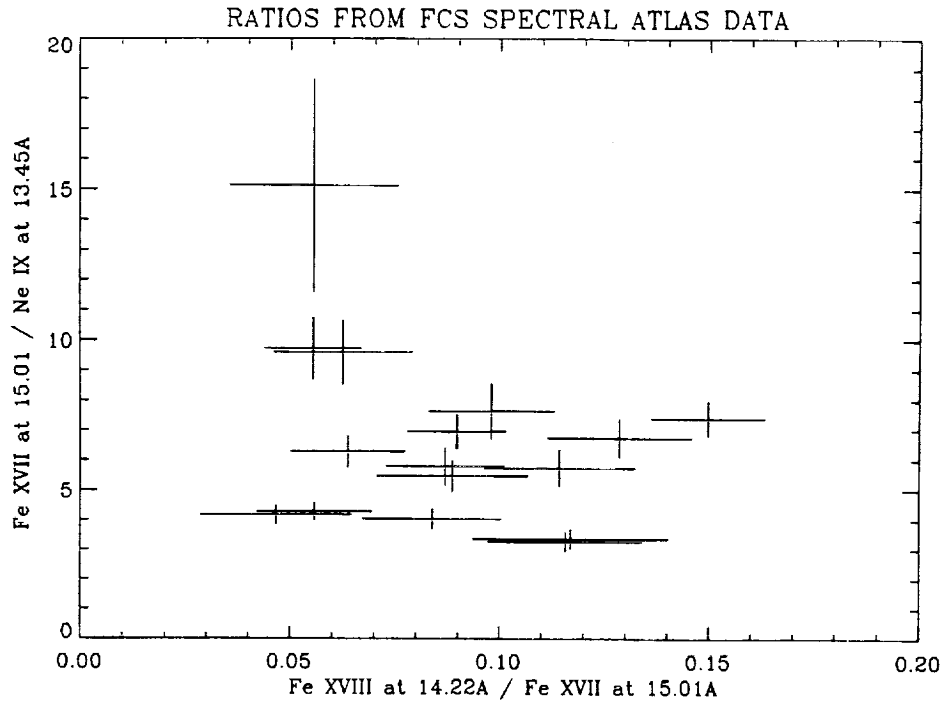


Figure 2 : Relation between escape probability and optical depth

(a)



(b)

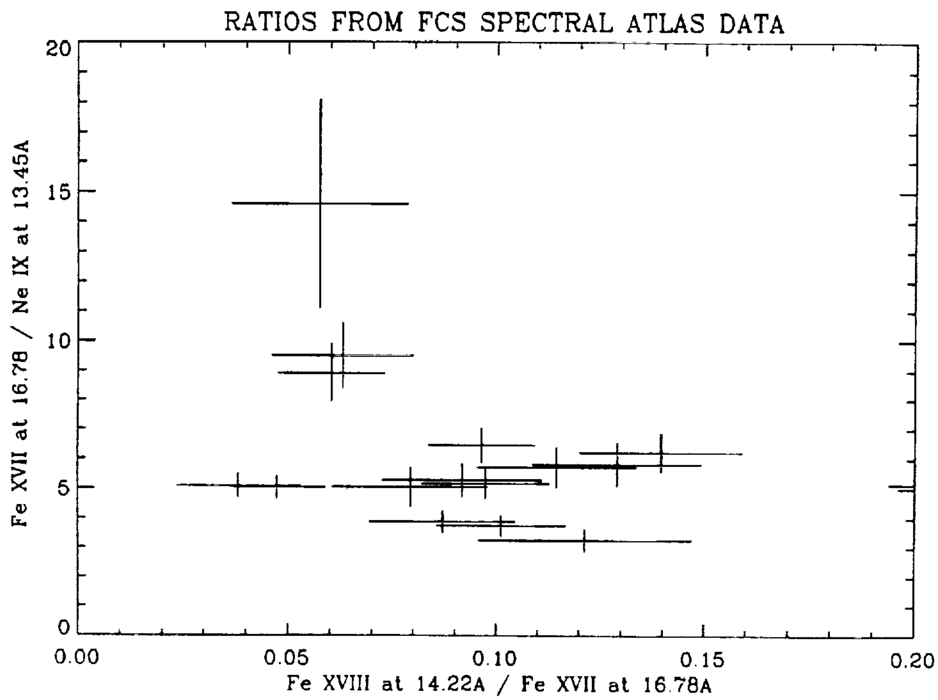


Figure 3: Comparison of scatter in FCS line ratios for two Fe XVII resonance lines. Part (a) shows plot for 15.01-Å line which is affected by resonance scatter; part (b) shows plot for 16.78-Å line which is unaffected.

Kofu symposium paper

IMPLICATIONS OF CORONAL ABUNDANCE VARIATIONS

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Abstract

High resolution soft X-ray spectra acquired by the Flat Crystal Spectrometer on *Solar Maximum Mission* have yielded exciting new information on the composition of the dynamic corona above solar active regions. In the brightest parts of these regions, the relative abundances of O, Ne, Mg, and Fe are found to vary from photospheric composition values to (and beyond) the typical "coronal" values found for solar energetic particles. This abundance variability complicates data interpretation but may ultimately offer new clues to the processes which supply and heat the corona.

1. Introduction

One of the big surprises to come from observations by the *Solar Maximum Mission (SMM)* Flat Crystal Spectrometer (FCS) was the large variation in elemental abundances found in quiescent and post-flare active regions, both from one region to another and for a given region from day to day (Strong *et al.* 1991). This variation may reflect a range in boundary conditions for the processes which heat and supply mass to coronal loops, and the detailed information on the variation should help constrain models of these processes. Abundance variability also has a large impact on data analysis and interpretation, and implications for theoretical models of coronal loops and astrophysical plasmas.

2. Observations and Analysis

Details of the FCS instrument are provided by Acton *et al.* (1980). After the *SMM* repair in April 1984, the FCS acquired an extensive spectral data base which includes long spectral scans at a single spatial location in the X-ray cores of solar active regions. Ratios of lines from the FCS long spectral scans can be used to determine relative abundances for certain elements such as O, Ne, Mg, and Fe and to look for abundance anomalies and variability.

13.

Kofu paper

For many *but not all* active regions, various line ratios (involving O VIII at 18.97 Å, Ne IX at 13.45 Å, Mg XI at 9.17 Å, Si XIII at 6.65 Å, Fe XVII at 16.78 Å, and Fe XVIII at 13.24 Å) give consistent values of T_e when the line emissivity calculations of Mewe et al. (1985) are used, provided the "adopted coronal" abundances of Meyer (1985) are substituted for photospheric abundances. Although observations made with modest spatial resolution require a differential emission measure (DEM) description of flaring loops, with a distribution of plasma over a range of temperatures, X-ray emission from quiescent active region loops appears to be well described by a single temperature or a range of temperatures narrow compared with the FCS measurement uncertainty (Saba and Strong 1991). Where the assumption of an isothermal plasma is valid, it is possible to use an abundance-independent line ratio diagnostic, such as the ratio of Fe XVIII to Fe XVII lines, to characterize the temperature of the plasma, and then in parallel to examine flux ratios of lines from different elements which are invariant or which vary only slowly with temperature over the temperature regime of interest to obtain the relative abundances of the respective elements. An example of a temperature-independent, abundance-diagnostic ratio is the ratio of the Fe XVII line at 15.01 Å to the Ne IX line at 13.45 Å, which is predicted by Mewe *et al.* to be flat over a broad range of active region temperatures, from about 2 MK to 7 MK.

3. Results

At the brightest portions of quiescent and postflare active regions where the FCS spectra were scanned, FCS line flux ratios reveal large variations in relative abundances of several elements. When the emissivity calculations of Mewe *et al.* are used to convert line flux ratios to elemental abundance ratios, the ratios of Fe/Ne, Fe/O, Mg/Ne, and Mg/O are found to range at least from the photospheric values to the nominal "coronal" values found in solar energetic particles (SEPs), a factor of 4 or 5 higher. Current ideas on coronal composition suggest an elemental fractionation based on first ionization potential (FIP) of the element, so that low-FIP elements (such as Fe and Mg) are enhanced in the corona relative to high-FIP elements (such as O and Ne), as compared with the photospheric composition. Other abundance research has shown that the enhancement factor is not a constant but depends on the kind of structure observed (Widing and Feldman 1989, Feldman *et al.* 1991), and may vary by an order of magnitude. The FCS results, as well as results from the P78-1 SOLEX instrument (McKenzie and Feldman 1991) show that the enhancement factor also varies dramatically even within nonflaring active regions. There is as yet no clear pattern in the abundance variability, although correlations are being sought in the data. When the observed ratios have nonphotospheric values, from the FCS spectral data alone it is not possible to tell if the low-FIP elements are enhanced or the high-FIP elements are depleted (or both), or whether all the heavy elements are enhanced (with respect to hydrogen), but the low-FIP elements by a greater amount. This issue is important for normalizing emission measures and for physical models, but it is not possible to measure directly the absolute abundance of an element relative to hydrogen using FCS line-to-continuum measurements since the FCS continuum is faint and difficult to differentiate from background.

4. Discussion

Previously, we have discussed the details of the FCS abundance variability results to date, and the effects of the ionization balance calculations chosen and possible systematic effects from resonance scattering (Saba and Strong 1992, 1993). Here we concentrate on the impact of the observed abundance variability on data analysis and interpretation.

Effect on data analysis and interpretation. Knowledge of the composition of the emitting plasma is implicitly assumed in deriving temperature, emission measure ($\equiv \int n_e{}^2 dV$, where n_e is the electron density and dV is the elemental emission volume), and DEM from

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emission line spectra. *Even if different temperature lines from a single ion species are used,* if there is an abundance difference with height, it will be difficult to understand emission measure with height without an independent measure of the element abundance relative to hydrogen. Temperatures and emission measures derived from broadband filter data are also significantly affected by abundance variability when line emission dominates the spectrum. For example, Waljeski *et al.* (1994) estimate that iron lines contribute about 80% of the filtered spectrum observed by the AS&E rocket instrument for active regions with the "adopted coronal" abundances of Meyer (1985). Multilayer images are dramatically affected by abundance variability. If abundances vary significantly between different types of structures as it appears, then there is no one-to-one correspondence between observed intensity and the amount of emitting material across the disk. Hence relative amounts of emitting material in different features may be impossible to interpret without independent abundance information from line spectra.

Role in theoretical calculations. In addition to its effect on first-level data analysis, abundance variability can also have a major impact on the theoretical calculations used to glean physics from the derived physical parameters. Identifying the emission mechanism often relies on a comparison of the relative emission in different wavebands, so that an assumption of incorrect abundances can lead to an incorrect source model. What may be less obvious is the extent to which abundances affect such calculations as the radiative loss function. An incorrect assumption of abundances can lead to an inaccurate radiative cooling time and an incorrect assessment of whether continuous energy input is required. The radiative loss curve also predicts the stability of coronal structures at a given temperature. Cook *et al.* (1989) have demonstrated the major differences between the radiative loss curves for photospheric and "adopted coronal" abundances and the dominant role that iron plays in the radiative losses at coronal temperatures and in the structural stability of coronal loops at different temperatures.

Constraints on element selection mechanism(s). Coronal abundance variability is currently an area of active research. Many of the observational facts, such as when abundance anomalies occur, the maximum range of variation of particular elements for given structures, and the relevant temporal and spatial scales for variability, are still largely unknown. The FCS spectra provide an excellent data base for addressing these issues. The detailed results of the ongoing FCS analysis should provide useful constraints on possible mechanisms for abundance variability. A variety of mechanisms have been proposed to explain the systematic differences between average coronal and photospheric composition, based on the idea that some element differentiation process operates in a temperature regime near 10,000 K where low-FIP elements have become ionized and are thus subject to electromagnetic fields while high-FIP elements remain essentially neutral. But the simple, single step-function distribution proposed to explain SEP composition does not seem to apply to all spectroscopic measurements of coronal abundances. One of the important tasks remaining is to understand how the SEP abundance results and spectroscopic measurements of coronal abundances fit together.

New information on the dynamic corona. The existing results from the FCS and other instruments suggest that the element selection mechanism is intimately tied to the physical processes for supplying and heating coronal loops. For some impulsive events and compact structures, the spectroscopically measured abundances are close to photospheric values. In other cases low-FIP elements appear enhanced relative to high-FIP elements by factors whose magnitude depends on as yet unknown factors. Perhaps the element selection mechanism, operating on a diffusion timescale, works with different efficiency under different circumstances. In other cases, there might be competing mechanisms at work, such as photoionization by a bath of soft X-rays in certain flares which show an enhanced abundance of neon (a high-FIP element), which does not fit the FIP pattern at all (see Murphy *et al.* 1991, and Schmelz 1993).

Using language more often associated with flare dynamics, we speculate that some of the large range of abundance variability corresponds to whether the coronal loops are filled by processes analogous to "explosive chromospheric evaporation" (which would presumably yield

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more photospheric abundances) or "gentle evaporation" (which might allow the low-FIP/high-FIP element selection mechanism to operate more efficiently). Although many important observational details of the abundance variability must still be worked out, it is already clear that our new picture of the highly dynamic corona must be expanded to include highly variable abundances before the data themselves can be understood and subsequent realistic models can be devised. At that point, the measured abundances of trace elements may become a useful diagnostic of the physical conditions and processes which fill coronal loops (with plasma of a given composition).

5. Conclusions

Abundance measurements from the FCS and other instruments suggest that there are large variations in the abundances of some elements in the corona, perhaps an order of magnitude in some cases. This will have a large impact on derivations of electron temperature and emission measure from spectral emission lines, from broadband filter data such as those from SXT on *Yohkoh*, and from multilayer images. If in fact the abundance of iron in the corona varies by a factor of ten between structures and within certain kinds of regions, the implications are extremely important for the interpretation of multilayer images from instruments such as the EUV Imaging Telescope on SOHO, for calculations of radiative cooling times, and for the structural stability of coronal loops as a function of temperature.

At present, the observed abundance variability is primarily a major complication to data analysis and interpretation. However, once it is better understood, it may provide a brand new diagnostic tool for probing the physical conditions in lower layers of the solar atmosphere and may offer new clues to the mechanisms of coronal supply and heating.

Acknowledgments We acknowledge support for this work from NASA contracts NAS5-30431 and NASW-4814 and the Lockheed Independent Research Program. Support for travel to the Kofu symposium was provided by the GSFC Solar Data Analysis Center through NASA contract NAS5-31235. The FCS data used here could not have been obtained without the repair of the *SMM* spacecraft by the crew of *Challenger* on mission 41-C. This paper is dedicated to the memory of the Francis R. Scobee, the pilot for that mission, and the commander of *Challenger*'s last flight.

References

1. Acton, L.W., *et al.*, 1980, *Sol. Phys.* **65**, 53.
2. Cook, J.W., Cheng, C.-C., Jacobs, V.L., and Antiochos, S.K., 1989, *Ap. J.* **338**, 1176.
3. Feldman, U., Widing, K.G., and Lund, P.A., 1991, *Ap. J. (Lett)*, **364**, L21.
4. McKenzie, D., and Feldman, U., 1991, *Ap. J.* **398**, 764.
5. Meyer, J.-P., 1985, *Ap. J. Suppl.* **57**, 173.
6. Mewe, R., Gronenschild, E.H.B.M., and van den Oord, G.H.J., 1985, Astron. Ap. **62**, 197.
7. Murphy, R.J., Ramaty, R., Koslovsky, B., and Reames, D.V., 1991, *Ap. J* **371**, 793.
8. Saba, J.L.R., and Strong, K.T., 1991a, *Ap. J.* **375**, 789.
9. Saba, J.L.R., and Strong, K.T., 1992, Proc. of the SOHO Workshop in Annapolis, Maryland, 25-28 August 1992, ESA SP-348, 347.
10. Saba, J.L.R., and Strong, K.T., 1993, *Adv. Space Res.* **13**, No. 9, 391.
11. Schmelz, J.T., 1993 *Ap. J.* **408**, 373.
12. Strong, K.T., Lemen, J.R., and Linford, G.A., 1991*Adv. Space Res.* **11**, No. 1, 151.
13. Waljeski, K. *et al.*, 1994, *Ap. J.*, in press.
14. Widing, K.G., and Feldman, U., 1989, *Ap. J.* **344**, 1046.

16.

A Reexamination of the Impact of Resonance Scattering on FCS Active Region Abundance Measurements.

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Recent work by Waljeski et al. (Ap. J., in press) suggests that the resonance scattering opacity for the Fe XVII line at 15.01 A is even larger than that found by Schmelz, Saba, and Strong (Ap. J. Letters, 398, L115, 1992), and that other bright soft X-ray resonance lines are also significantly affected by resonance scattering under normal active region conditions.

Because of the potential impact of these results on active region abundance measurements from the *SMM* Flat Crystal Spectrometer (FCS), the importance of resonance scattering is being reexamined for a number of active regions at a variety of disk locations. The observed ratio of the most affected line, Fe XVII at 15.01 A, to the virtually unaffected Fe XVII line at 16.78 A is compared to the theoretical ratio predicted by Bhatia and Doschek (Atomic Data and Nucl. Data Tables, 52, 1, 1992) in the absence of resonance scatter. The corresponding optical depth for the 15.01 A line is computed by using the relationship between the optical depth and the "homogeneous escape probability" of Kastner and Kastner (J. Quant. Spectrosc. Rad. Transf., 44 (2), 275, 1990); the opacities of other lines are scaled by simple formulae involving the respective atomic data.

Preliminary results indicate optical depths about a factor of two less than those reported by Waljeski et al., so that the depletion from scattering for lines other than the 15.01 A line is less than the uncertainties if the "adopted coronal" abundances of Meyer (Ap. J. Suppl. 57, 173, 1985) apply. If the inferred abundances are photospheric, however, as has been reported for some active regions by McKenzie and Feldman (Ap. J., 389, 764, 1992) and Saba and Strong (e.g., Adv. Space Res., 13, No. 9, 391, 1993), the effects for the O VIII line at 18.97 A and the Ne IX line at 13.45 A are significantly larger and could impact the abundance determinations.

The observed line flux ratios are adjusted and the relative abundances for Mg, Fe, O, and Ne recomputed as necessary, and the normalization of the abundances with respect to hydrogen is constrained by means of a technique proposed by Waljeski et al. which uses the resonance scattering opacity, the emission measure, the mean electron density derived by the method of Schmelz et al., and an estimate of the path length. Information on the absolute abundances is crucial for interpreting coronal data and for understanding the mechanism(s) responsible for coronal/photospheric composition differences, but it is generally otherwise unavailable for active region spectroscopic abundance measurements.

1. 1994 Spring Meeting
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Abstract submitted for July 1992 COSPAR Meeting in Hamburg, Germany for invited review in session E2.1 on *Element Abundance Variations in the Sun and the Heliosphere*

SPECTROSCOPIC MEASUREMENTS OF ELEMENT ABUNDANCES IN THE SOLAR CORONA: VARIATIONS ON THE FIP THEME

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Solar wind and solar energetic particle (SEP) data yield systematic differences between elemental abundances in the corona and in the photosphere related to the first ionization potential (FIP) of the elements: low-FIP elements are preferentially enhanced relative to high-FIP elements by about a factor of four. Spectroscopic studies of the inner corona show that such a pattern may apply on average but not in detail for coronal loops: substantial abundance differences occur between different types of coronal structures, and variations have been found from one active region to another and over time in the same region; further, in some flares, anomalies such as enhanced Ne:O ratios, distinctly at odds with the FIP pattern, show that a competing element selection mechanism sometimes operates.

Details of the observed abundance variability – such as the magnitude of the variations, correlations with other properties of the given coronal structure, and the relevant temporal and spatial scales – may give important clues to the processes which supply and heat the corona or they may reflect the changing physical conditions where those processes take place. Abundances like those in the photosphere might result when coronal loops are filled by a rapid, "explosive" process, while SEP-like abundance enhancements might result when loops are filled more gradually, so that the FIP element selection mechanism has had time to operate more efficiently. At present, abundance variability is primarily a major complication to data analysis and interpretation. However, once it is better understood, it may provide a new diagnostic tool for probing the lower layers of the solar atmosphere.

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2. Meeting/ Session E2.1
   Element Abundance Variations in the Sun and the Heliosphere
3. MSO: Dr. A. Gabriel
4. Only standard equipment needed but two overhead projectors would be useful.
5. Oral presentation (invited)

NASA	REPORT DOCUMENTATION PAGE 19 (IN LIEU OF NASA FORM 1626)	
1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Coronal Abundances and their Variations Progress report - for the period June 1993 - April 1994		5. REPORT DATE 15 April 1994
		6. PERFORMING ORGANIZATION CODE: 0/91-30
7. AUTHOR(S) J. L. R. Saba		8. PERFORMING ORGANIZATION REPORT NO:
		10. WORK UNIT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lockheed Palo Alto Research Labs B/252 Solar & Astrophysics Laboratory 0/91-30 3251 Hanover Street , Palo Alto Ca. 94304		11. CONTRACT OR GRANT NO. NASW-4814
12. SPONSORING AGENCY NAME AND ADDRESS NASA Headquarters Solar Physics Branch Space Physics Division Washington, D.C. 20546		13. TYPE OF REPORT AND PERIOD COVERED Progress report for the period June 1993 - April 1994
		14. SPONSORING AGENCY CODE NASA HQ/ CODE SS
15. SUPPLEMENTARY NOTES		

16. ABSTRACT
This contract supports the investigation of elemental abundances in the solar corona, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer on NASA's Solar Maximum Mission. The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, and information on the extent and circumstances of their variability. This report is a summation of the data analysis and reporting activities which occurred during the first ten months of the contract, 15 June 1993 to 15 April 1994.

17. KEY WORDS (SUGGESTED BY AUTHOR(S))	18. DISTRIBUTION STATEMENT
X-Ray, Spectra, Corona, Composition	Space Science, Solar Physics

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO OF PAGES	22. PRICE
None	None	19	

For sale by: Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402-0001